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Study of Neutral-Charged Particle Correlations in High Energy Collisions

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ABSTRACT

Recent experiments at Serpukhov, NAL, and CERN indicate a strong correlation between neutral and charged pions produced in high energy collisions, in contrast to the trend shown by data at lower energies. This study of the energy and charge dependence of these correlations indicates that they do not depend upon the initial state particles and that they are in reasonable agreement with the critical fluid gas model. These high energy correlation data are also studied in terms of a semi-inclusive Koba-Nielsen-Olesen scaling relation.

One of the striking features of high energy collisions as revealed by recent Serpukhov, NAL, and CERN ISR data is the strong correlation between neutral and charged pions. The average number of π^0's produced in a pp collision is observed to depend upon the number of associated charged particles produced. This correlation at high energy differs from that observed at lower energies. In this letter, we characterize the energy dependence of this correlation and demonstrate that this correlation increases with energy but is independent of the initial colliding particles. We study this neutral and charged particle correlation in terms of current theoretical models and in the framework of a new form of Koba, Nielsen and Olesen (KNO scaling which gives definite predictions for the semi-inclusive reaction

$$pp \to \pi^0 + n \text{ charged particles}. \qquad (1)$$

In addition, comparisons are made with the correlations between various charged particles in the final states.

Figure 1 shows the average number of neutral pions, $\langle n_{\pi^0} \rangle$, as a function of the associated number of negative particles, n_-, at various incident momenta ranging from 12 to 1500 GeV/c for all the available data[1] from pp, $\pi^\pm p$, and $\pi^- n$ interactions. We note that the correlation between π^0 and π^- (for all incident momenta up to ISR energies, π^- production dominates over that for K^- and $\bar{p}$) increases monotonically with incident laboratory momentum. To investigate the energy dependence of these correlations, we parameterize the trend of the neutral and negative pion correlation as shown in Fig. 1 by the following expression:

$$\langle n_{\pi^0} \rangle = \alpha n_- + \beta \tag{2}$$

where α, β are energy dependent parameters. With regards to this form, we note that it is a form that renders a simple meaning to the parameter α which indicates the amount of π^0 that is coupled to π^-. (For example, in ρ^- production, every π^0 is coupled to π^- and $\alpha = 1$.) We should point out, however, that with improved statistics in the distribution of $\langle n_{\pi^0} \rangle$ versus n_-, one might discern deviations from this linear form, especially for small or large charged multiplicity. For small n_-, deviations may arise from diffraction-like processes.[2] At the other extreme, departures may come from conservation of energy. In these cases, one can confine the linear parameterization to the intermediate values of n_- which, nevertheless, characterize the bulk of pion production in high energy collisions. However, with the exception of the 205 GeV/c data[1] the present statistical accuracy of the data does not warrant this.

In Fig. 2, the parameter α is plotted as a function of E which is the available energy[3] in the CM system. The πN data are in good agreement with the pp data and, therefore, indicate that these correlations do not depend on the initial state particles. To understand the dependence of α on E, we are motivated by the recent success of the gas-fluid analogy. Arnold and Thomas[4] have shown that the properties of a one-dimensional gas can be profitably applied to high energy collisions because of the general limitation in transverse momentum. This model has been generalized by Thomas[5] to high energy interactions in which two kinds of particles are produced. These particles are treated as Van der Waal fluids interacting at the critical point. The prediction of this model is shown as the solid curve in Fig. 2 and is in reasonable agreement with the data. Two features are to be noted. In this model, the independence of the correlation on the initial state particles is to be expected and the negative value of α observed at low energy is a reflection of energy conservation which necessarily restricts $< n_{\pi^0} >$ once the charged pions are produced. At incident momenta above ~ 10 GeV/c, the energy constraints become less important and any increase in α reflects dynamical correlation.

In order to compare the relative strengths of these $\pi^0\pi^-$ correlations with those between a pair of charged final state particles, we now express these correlations in terms of the Mueller parameters.[6] In particular, the two body correlation parameter f_2 is defined as

$$f_2 = \begin{cases} < n(n-1) > - < n >^2 & \text{for } n_1 = n_2 = n\,, \\ < n_1 n_2 > - < n_1 > < n_2 > & \text{for } n_1 \neq n_2\,. \end{cases}$$

In Fig. 3 we show the various f_2^{ab} parameters in pp collisions as a function of incident laboratory momentum (a and b indicate the charge of the two types of particles; cc indicates the correlation between charged particles regardless of the sign of their charge). We note that not all of the parameters presented in Fig. 3 are independent, for example, for pp collisions $f_2^{--} = f_2^{++} + 2$, $f_2^{+o} = f_2^{-o}$, and $f_2^{cc} = 4f_2^{+-} - < n >$. Furthermore, f_2^{oo} is not known, at present, as there are no data on the π^o multiplicity distributions in high energy collisions. We observe that the strength of the $\pi\pi$ correlation becomes increasingly more positive with higher energy. In particular, f_2^{-o}

is significantly different from zero for $P_{lab} > 50$ GeV/c and is still increasing at the highest energies presently available. These data also show that at high energy the following ordering is obtained:

$$f_2^{cc} > f_2^{+-} > f_2^{-o} > f_2^{--} ,$$

which implies that, after integration over all transverse and longitudinal momenta, a neutrally charged pair of particles is more strongly correlated than a singly charged pair or a doubly charged pair. We have studied these f_2 parameters in terms of both a simple fragmentation model[2] and a critical fluid model.[5] The results show that the data are in fair agreement with the critical fluid model which predicts a $(\ln s)^{3/2}$ dependence with energy whereas the simple fragmentation model gives a $s^{1/2}$ dependence which seems too strong in the present energy range. Furthermore, f_2^{oo} is predicted to be equal to f_2^{+-} for the fragmentation model, while $f_2^{oo} \approx f_2^{-o}$ in the critical fluid model. This suggests that a measure of f_2^{oo} at high energy could prove a useful discriminator of high energy production processes.

We have further examined the energy and charge dependence of these correlations in the framework of a semi-inclusive scaling law proposed by Koba, Nielsen and Olesen (KNO).[7] The semi-inclusive scaling law has recently been shown to work well for the charged multiplicity distributions in hadron-proton collisions,[8, 9] although there are indications that it is only obeyed by data for a limited energy range.[9] We now derive a new form of KNO scaling for the semi-inclusive reaction given in (1) and compare the prediction with the available data and other models.

We start with the expression[7]

$$\langle n \rangle \ \langle n_o \rangle \ \frac{\sigma(n, n_o)}{\sigma_{inel}} = \psi\left(\frac{n}{\langle n \rangle}, \frac{n_o}{\langle n_o \rangle}\right), \tag{3}$$

where $\sigma(n, n_o)$ is the cross section for producing n charged particles and n_o neutral particles, σ_{inel} is the total inelastic cross section, $\langle n \rangle$ and $\langle n_o \rangle$ are the average number of charged and neutral particles respectively, and ψ is an energy independent function which depends only on $\frac{n}{\langle n \rangle} = z$ and $\frac{n_o}{\langle n_o \rangle} = y$. As discussed above, there are no available data on $\sigma(n, n_o)$. However, data on the semi-inclusive reaction (1) provide a measurement of the inclusive π^o cross section as a function of the charged particle multiplicit

$$\sigma_n(\pi^o) \equiv \sum_{n_o} n_o \, \sigma(n, n_o). \tag{4}$$

By combining (3) and (4), we obtain

$$\sigma_n(\pi^o) = \frac{\langle n_o \rangle \, \sigma_{inel}}{\langle n \rangle} \sum_{n_o} \frac{n_o}{\langle n_o \rangle^2} \ \psi(z, y)$$

$$\xrightarrow[s \to \infty]{} \frac{\langle n_o \rangle \, \sigma_{inel}}{\langle n \rangle} \int y \, dy \ \psi(z, y) \equiv \frac{\langle n_o \rangle \, \sigma_{inel}}{\langle n \rangle} \, \Phi_2(z) .$$

We thus derive the following scaling law for semi-inclusive π^o production:

$$\frac{\langle n \rangle}{\langle n_{\pi^o} \rangle} \ \frac{\sigma_n(\pi^o)}{\sigma_{inel}} = \Phi_2\left(\frac{n}{\langle n \rangle}\right) \tag{5}$$

analogous to the KNO scaling equation[7]

$$\langle n \rangle \ \frac{\sigma_n}{\sigma_{inel}} = \Phi_1\left(\frac{n}{\langle n \rangle}\right), \tag{6}$$

where σ_n is the cross section for producing n charged particles. In Fig. 4 we test this scaling prediction by plotting the high energy pp data (P_{lab} > 50 GeV/c) as a function of $n/\langle n\rangle = z$. Since it has been shown[9] that the $\bar{p}p$ data[1] at 15 GeV/c also satisfy the same form of KNO scaling (Eq. 6) as the pp data, the π^o data from this experiment have also been included. Figure 4 thus indicates that the data suggest a single function, $\Phi_2(z)$, independent of both the initial state particles and, for the limited range available, the incident energy. The solid curve in Fig. 4 represents a least-squares fit to the data using the form $\Phi_2(z) = b \exp(\sum_{i=1}^{m} a_i z^i)$. The result for m = 4, and $0 \leqslant z \leqslant 2.9$ (yielding $\chi^2/NDF = 16.8/29$) is:

$$\Phi_2(z) = 0.072 \exp(7.30z - 5.61z^2 + 1.62z^3 - 0.22z^4).$$

It should be emphasized that this function may change in form with higher energy; however, for the scaling law to be meaningful, there should still be a single function for all hadron-hadron collisions. It is interesting to note that this scaling equation (5), with the same Φ_2 as for π^o, will also hold for K_S^o production data, insofar as the ratio of K_S^o/π^o is found to be independent of the charged multiplicity in high energy pp collisions.[1]

It can be shown that Eqs. (5) and (6) are equivalent to the following ratios of moments

$$\frac{\langle n_o n^q\rangle}{\langle n_o\rangle \langle n\rangle^q} \equiv c_{1,q} \quad \text{and} \quad \frac{\langle n^{q+1}\rangle}{\langle n\rangle^{q+1}} \equiv d_{q+1} \qquad (7)$$

being energy independent for q = 1, 2, 3, etc. The first four moments are found to be constant and their averages are listed in Table I. We note[10] that

$d_q < c_{1,q} < d_{q+1}$, which indicates that neutral and charged particles are correlated but that this correlation is not as strong as that between just charged particles. These $c_{1,q}$ and d_q moments can easily be related to the Mueller parameters. In particular, for q = 1 we have

$$f_2^{cc} = (d_2 - 1 - \frac{1}{<n>}) <n>^2 \underset{s\to\infty}{\sim} 0.25 <n>^2$$

$$f_2^{+-} = \frac{1}{4} (d_2 - 1) <n>^2 \underset{s\to\infty}{\sim} 0.06 <n>^2$$

$$f_2^{-o} = \frac{1}{2} (c_{1,1} - 1) <n> <n_o> \underset{s\to\infty}{\sim} 0.07 <n> <n_o>$$

$$f_2^{--} = \frac{1}{4}(d_2 - 1 - \frac{2}{<n>} + \frac{4}{<n>^2}) <n>^2 \underset{s\to\infty}{\sim} 0.06 <n>^2$$

As $<n>$ and $<n_o>$ are generally assumed to increase logarithmically with energy, the semi-inclusive scaling law predicts the following behavior for f_2 at very high energies:

a) $f_2 \propto (\ln s)^2$, as compared to a $(\ln s)^{3/2}$ dependence in the critical fluid model and a $s^{1/2}$ dependence in the fragmentation model, and

b) $f_2^{cc} = 4 f_2^{+-} = 4 f_2^{--}$ and, if we further assume $<n> \simeq 2 <n_o>$, we have $f_2^{+-} \approx f_2^{--} > f_2^{-o}$.

The second prediction is particularly interesting as the charge ordering of the correlations differs from that which is observed for the data below 303 GeV/c.

In summary, the results of the present analysis indicate that there is a monotonically increasing energy dependence to the $\pi^0\pi^-$ correlation which does not seem to depend on the identity of the initial state particles. The relative strengths of the $\pi\pi$ correlations show that at present energies neutral pairs are more strongly correlated than charged pairs. These two phenomena are accounted for reasonably well by the critical fluid model and in the framework of Koba-Nielsen-Olesen scaling. The latter however predicts a $(\ell n\ s)^2$ dependence for all f_2 and a change in the ordering of the charge dependence at much higher energies.

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REFERENCES

[1] The following data are used:

12 GeV/c pp: J. H. Campbell et al., ANL/HEP 7311 (1973)

15 GeV/c $\bar{p}p$: F. T. Dao and J. Lach, Washington APS Meeting, Bull. APS 18, 694 (1973)

19 GeV/c pp: H. Bøggild et al., Nucl. Phys. B27, 285 (1971)

24 GeV/c π^+p: A. Erwin et al., Contribution to the XVI International Conference on High Energy Physics, Batavia (1972)

25 GeV/c π^-p: J. W. Elbert et al., Nucl. Phys. B19, 85 (1970)

40 GeV/c π^-p and π^-n: O. Balea et al., Nucl. Phys. B52, 414 (1973)

69 GeV/c pp: P. Granet et al., Contribution to the International Conference on Multiparticle Production, Vanderbilt University, Nashville (1973)

102 GeV/c pp: J. W. Chapman et al., Phys. Rev. Letters 29, 1686 (1972)

205 GeV/c pp: G. Charlton et al., Phys. Rev. Letters 29, 515 (1972) and Phys. Rev. Letters 29, 1759 (1972); 30, 1192 (1973)

303 GeV/c pp: F. T. Dao et al., Phys. Rev. Letters 30, 1151 (1973)

1500 GeV/c pp: K. R. Schubert et al., Proceedings XVI International Conference on High Energy Physics, Batavia, Vol. 1, 244 (1972).

[2] E. L. Berger, D. Horn and G. H. Thomas, Phys. Rev. D7, 1412 (1973). This paper also contains a review of several other models for $\langle n_{\pi^0} \rangle$ vs n_-.

[3] We define E as the total energy ($\sqrt{s}$) minus the baryon masses in the initial state. However in low energy $\bar{p}p$ collisions where the annihilation process dominates, we should use 2E as the available energy to account for the

hsence of leading particles which do not affect the correlation mentioned the text but generally take away ~50% of the total energy. For higher nergy $\bar{p}p$ collisions where both annihilation and non-annihilation processes re present, the definition of available energy becomes less clear. A preiminary study of the associated π^0 production at 15 GeV/c $\bar{p}p$ (see Ref. 1) hows that π^0 and π^- have as much correlation as in an equivalent pp system t 69 GeV/c.

R. C. Arnold and G. H. Thomas, ANL/HEP 7257 (to be published in Phys. Letters).

G. H. Thomas, ANL/HEP 7302 (to be published in Phys. Rev.).

A. H. Mueller, Phys. Rev. D4, 150 (1971).

Z. Koba, H. B. Nielsen, and P. Olesen, Nucl. Phys. B40, 317 (1972).

P. Slattery, Phys. Rev. Letters 29, 1624 (1972) and Phys. Rev. D7, 2073 (1973).

[9]F. T. Dao, J. Lach, and J. Whitmore, NAL Preprint NAL-Pub 73/37-EXP.

[0]This inequality indicates that a recent theoretical assumption of A. Krzywicki, in Ref. TH. 1633-CERN Preprint (1973), as to the dominance of isosinglet exchange in the forward scattering amplitude which predicts $c_{1,q} = d_{q+1}$ is not warranted at present energies. In fact, we find empirically that the data are consistent with the relation $2c_{1,q} = d_q + d_{q+1}$.

TABLE I

Ratio of Moments

q	$\langle n_o n^q \rangle / \langle n_o \rangle \langle n \rangle^q$	$\langle n^{q+1} \rangle / \langle n \rangle^{q+1}$
1	1.14 ± 0.02	1.25 ± 0.01
2	1.51 ± 0.04	1.82 ± 0.02
3	2.26 ± 0.11	2.96 ± 0.05
4	3.69 ± 0.25	5.27 ± 0.11

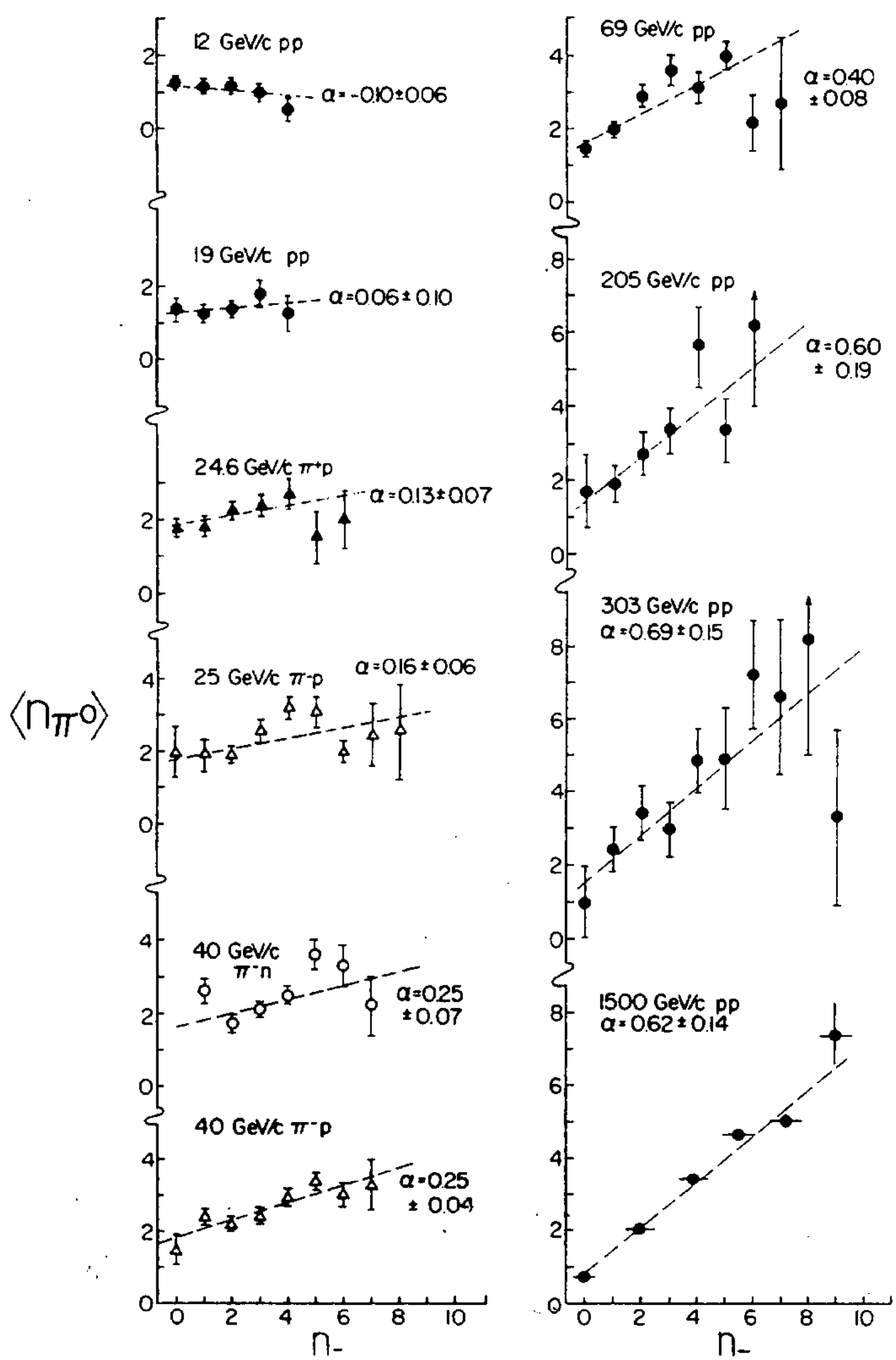
FIGURE CAPTIONS

Fig. 1 Average number of neutral pions versus negative charged multiplicity for pp and πN collisions. The α's are obtained from fitting the data to $< n_{\pi^o} > = \alpha n_- + \beta$.

Fig. 2 α as a function of the available energy E (see text). The solid curve is a prediction of the critical fluid model (see Ref. 5).

Fig. 3 The correlation parameters, f_2, as a function of the incident laboratory momentum for pp collisions. The superscripts refer to the charge of the two final state particles. The solid (dashed) curves are predictions from a fragmentation (critical fluid) model.

Fig. 4 Plot of $< n > \sigma_n(\pi^o)/< n_{\pi^o} > \sigma_{inel}$ versus $n/< n >$ for the reactions pp, $\bar{p}p \rightarrow \pi^o +$ n charged particles. The solid curve is an empirical fit to the data (see text).



12 GeV/c pp
α = -0.10 ± 0.06
19 GeV/c pp
α = 0.06 ± 0.10
24.6 GeV/c π+p
α = 0.13 ± 0.07
25 GeV/c π-p
α = 0.16 ± 0.06
40 GeV/c π-n
α = 0.25 ± 0.07
40 GeV/c π-p
α = 0.25 ± 0.04
69 GeV/c pp
α = 0.40 ± 0.08
205 GeV/c pp
α = 0.60 ± 0.19
303 GeV/c pp
α = 0.69 ± 0.15
1500 GeV/c pp
α = 0.62 ± 0.14
⟨n_π0⟩
n_

Fig. 1

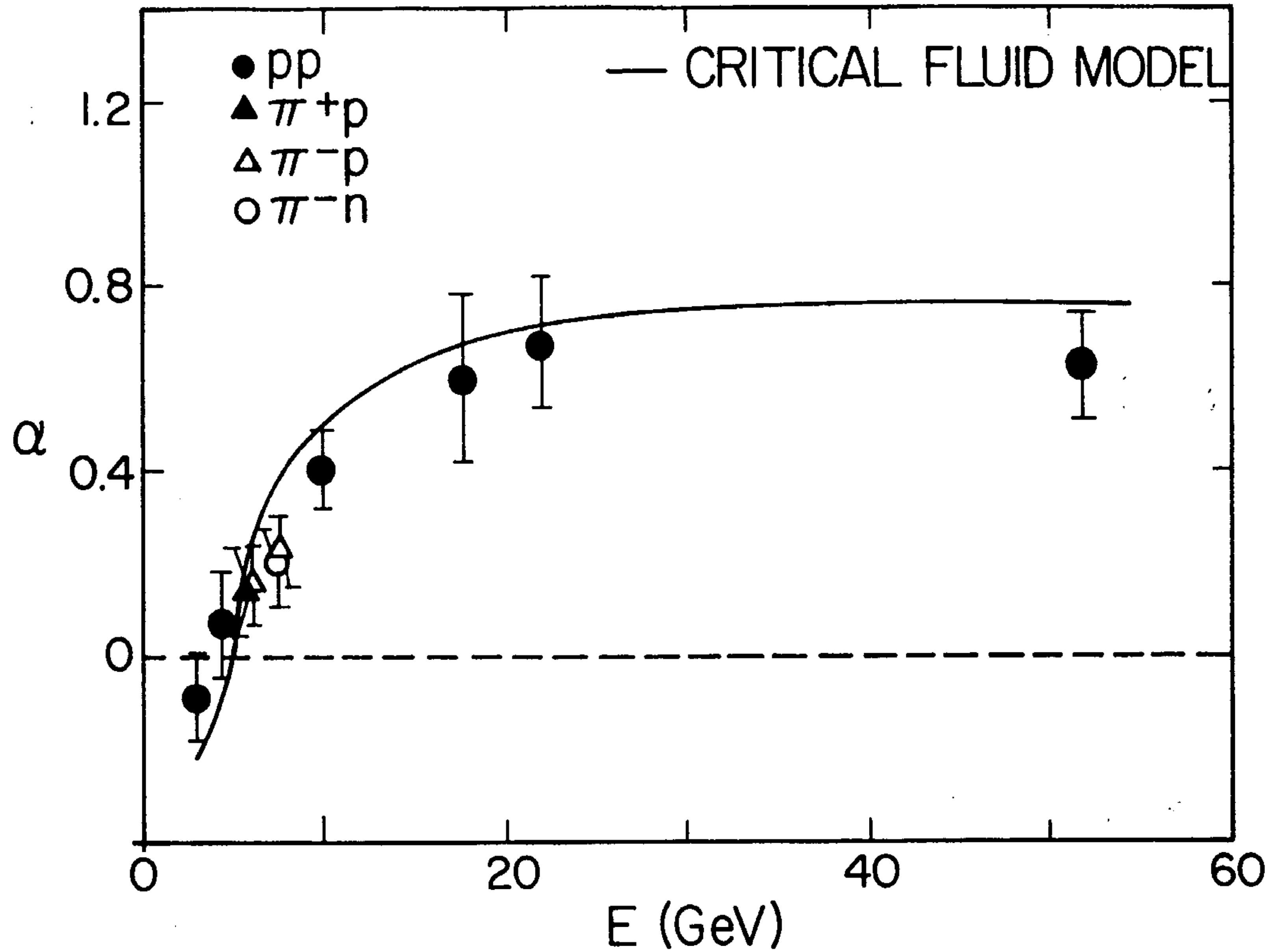
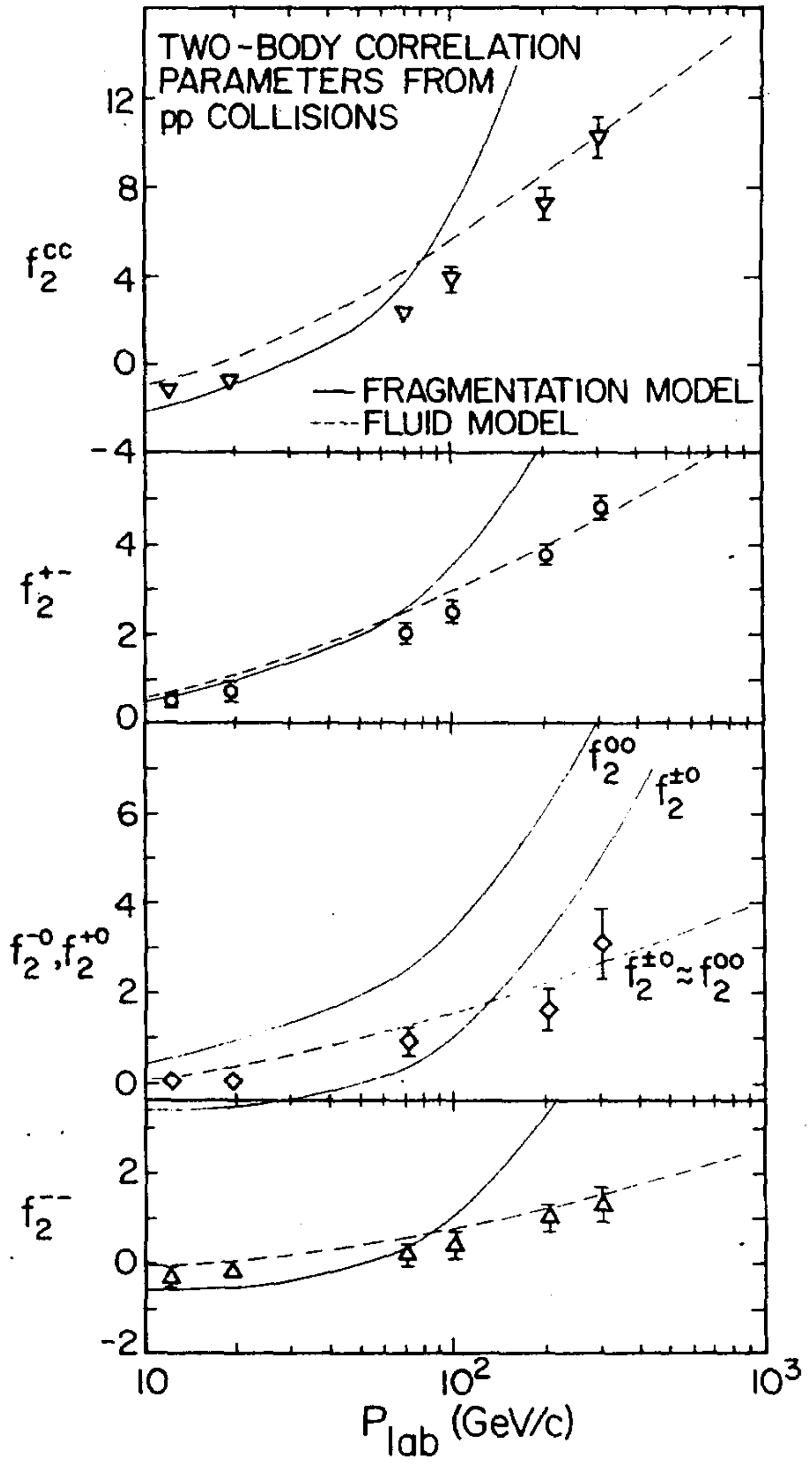
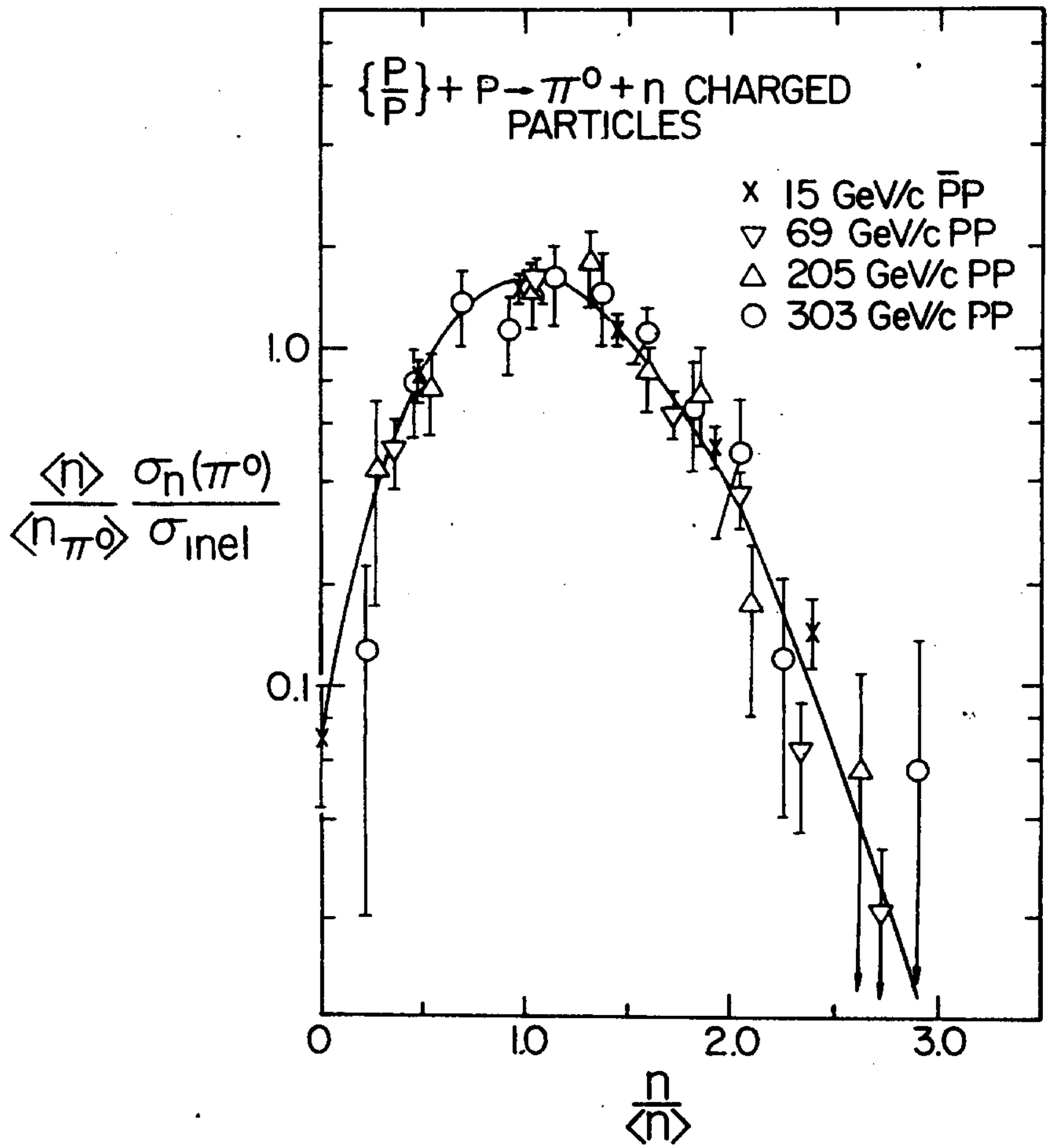


Fig. 2



TWO-BODY CORRELATION PARAMETERS FROM pp COLLISIONS
FRAGMENTATION MODEL
FLUID MODEL
f_2^{cc}
f_2^{+-}
f_2^{-0}, f_2^{+0}
f_2^{00}
$f_2^{\pm 0}$
$f_2^{\pm 0} \approx f_2^{00}$
f_2^{--}
P_{lab} (GeV/c)

Fig. 3



$\left\{\begin{matrix}\bar{P}\\P\end{matrix}\right\} + P \to \pi^0 + n$ CHARGED PARTICLES
x 15 GeV/c $\bar{P}P$
▽ 69 GeV/c PP
△ 205 GeV/c PP
○ 303 GeV/c PP
1.0
0.1
$\frac{\langle n \rangle}{\langle n_{\pi^0} \rangle} \frac{\sigma_n(\pi^0)}{\sigma_{inel}}$
0
1.0
2.0
3.0
$\frac{n}{\langle n \rangle}$

Fig. 4